

National Aeronautics and Space Administration



NASA Hydrogen and Fuel Cell Perspectives

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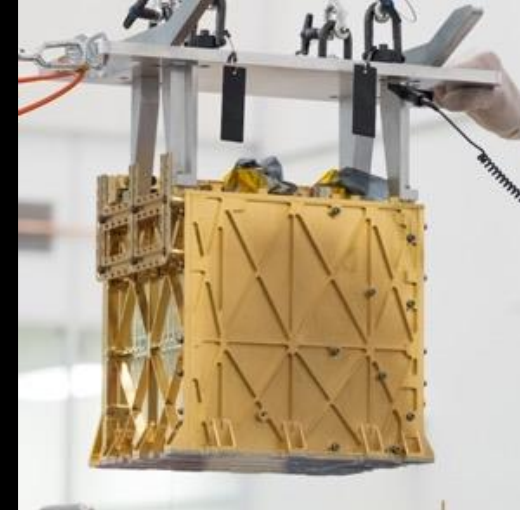


Presentation Overview

- Provide a background of NASA Hydrogen activities technologies for Aerospace applications:
 - Reactant generation
 - ❖ Environmental Control and Life Support (ECLSS)
 - ❖ In Situ Resource Utilization (ISRU)
 - ❖ Energy Storage / Hydrogen Economy
 - Reactant Transfer and Storage
 - ❖ Cis-lunar propellant infrastructure
 - Power Generation / Energy Storage
 - ❖ Primary Fuel Cells (Power)
 - ❖ Regenerative Fuel Cells (Energy Storage)

Mars Oxygen ISRU Experiment (MOXIE)

Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.



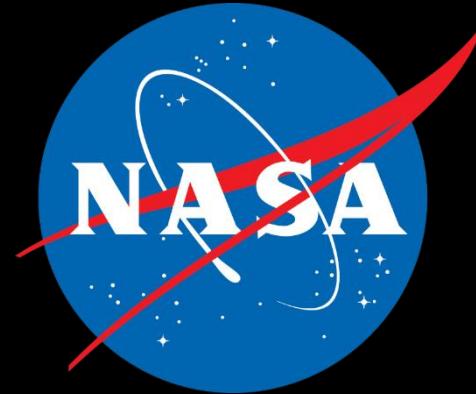
Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)

Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage.

Hydrogen Activities Within NASA

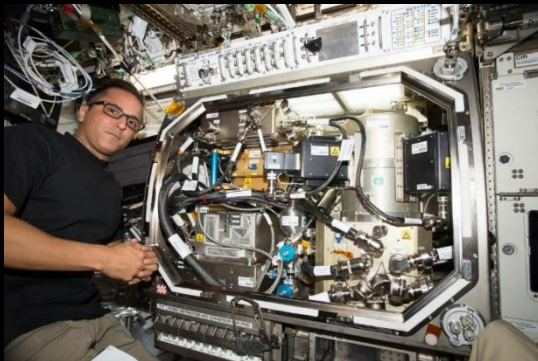
Reactant Generation

- *Electrochemically dissociating water into gaseous hydrogen and oxygen*
 - Environmental Control and Life Support Systems (ECLSS)
 - Energy Storage
 - ISRU
 - Contaminated Water Sources (ISRU)
- *Recover raw materials from local sources*
 - Water (ice) Mining
 - Contaminated Water Processing
 - Regolith Processing



Power Production

- *Propellants*
 - Launch Vehicles
 - Mars/Lunar Landers
- *Fuel hydrogen-based fuel cells*
 - Lunar/Mars surface systems
 - Urban Air Mobility
- *Metal Processing*
- *Refrigerants*



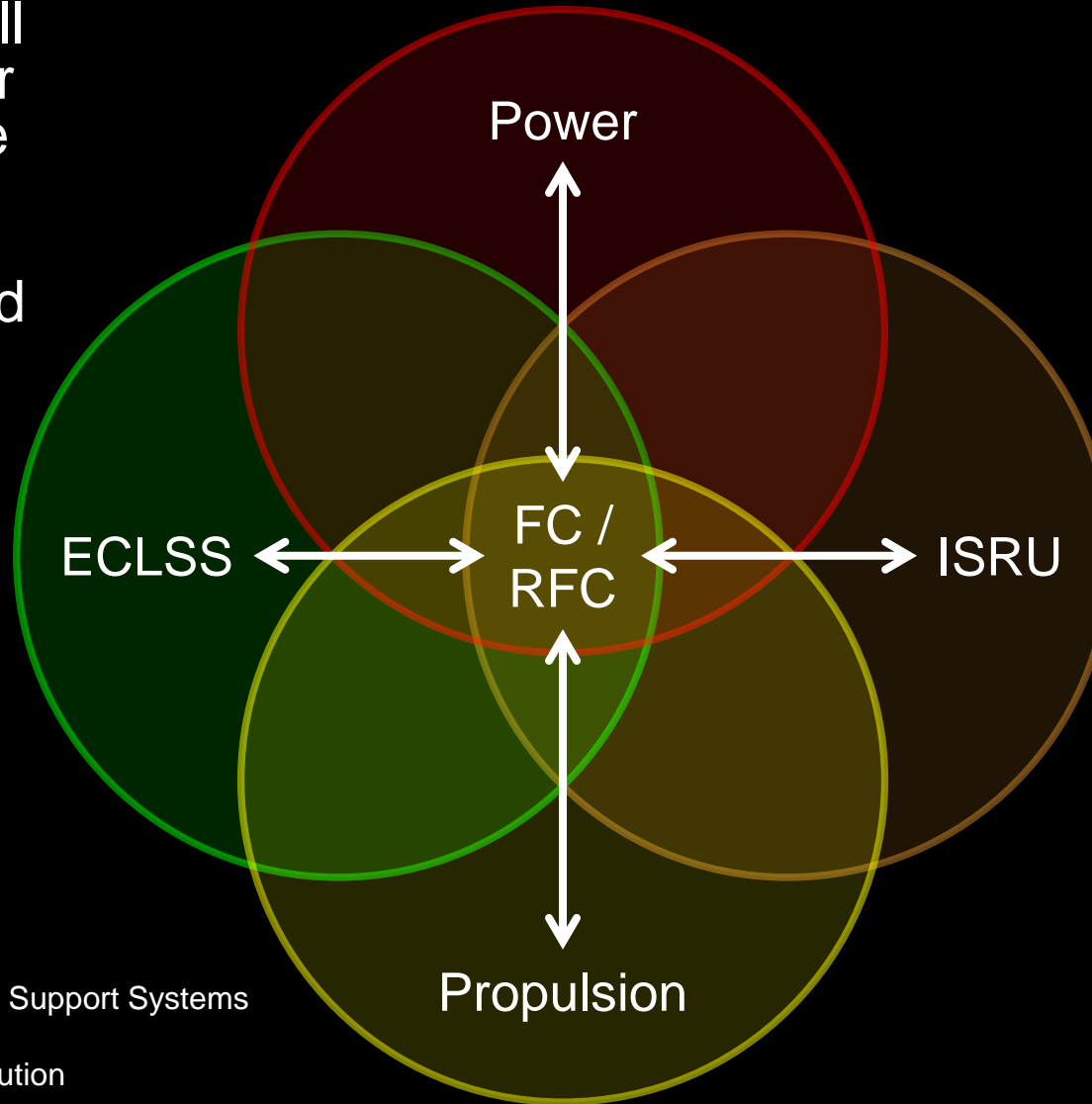
Transfer and Storage

- *Hydrogen Management*
 - Cryogenic Fluid Transfer in μ -gravity
 - Cryogenic Storage and Transfer
- *Extend storage duration of cryogenic fluids*
 - Zero-Boil-off Tanks
 - High-efficiency Efficiency Cryo-coolers



Electrochemical Interoperability

With their core fuel cell and water electrolyzer technologies, multiple electrochemical applications share common reactants and power/energy requirements.



Legend

ECLSS = Environmental Control and Life Support Systems

ISRU = In Situ Resource Utilization

PMAD = Power Management and Distribution

RFC = Regenerative Fuel Cell

TRL = Technology Readiness Level

* = Application-Specific Technology Readiness Level

Aerospace

Electrochemistry Options

1) Proton Exchange Membrane (PEM)

- Low Temperature (-4 to 85 °C)
- Reactant Cycles
 - $\text{H}_2 / \text{O}_2 / \text{H}_2\text{O}$
- TRL 5⁺ / 9^{*}
- HT-PEM TRL 2^{*}

2) Solid Oxide

- Reactant Cycles
 - $\text{H}_2 + \text{O}_2 \leftrightarrow \text{H}_2\text{O}$
 - $(\text{CH}_4 + \text{CO} + \text{H}_2) + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2$
- Anionic Conducting (O^{2-})
- Fuel cell mode TRL 3⁺ (TRL 9 terrestrial)
- Electrolysis mode TRL 9^{*}
- Protonic Conducting (H^+) TRL 3

3) Alkaline

- Reactant Cycles
 - $\text{H}_2 + \text{O}_2 \leftrightarrow \text{H}_2\text{O}$
- TRL 3⁺ (TRL 9 terrestrial)

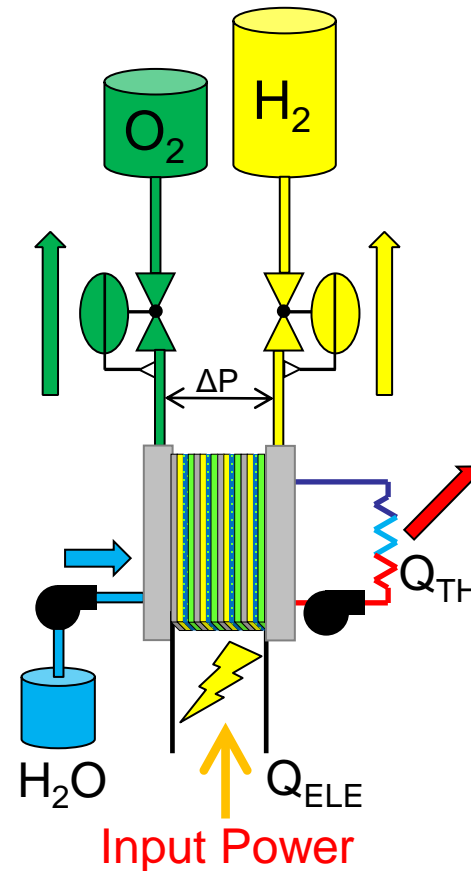
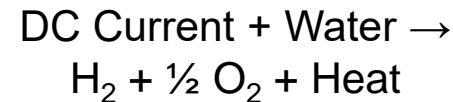
Basic Electrochemical Systems: Electrolysis



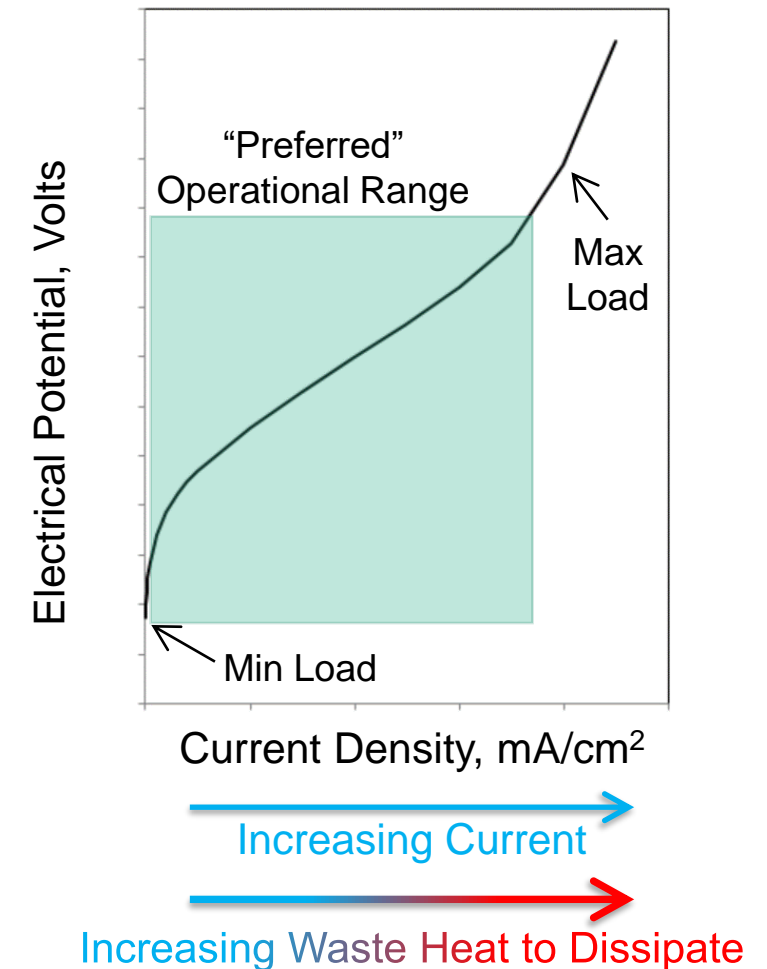
Electrolysis

- Hydrogen production process for over 100 years
- **Green** technology if power source is renewable
- Fluidic analogy
 - Current \sim H₂ production rate
 - Voltage \sim H₂ production efficiency
- Source water purity very dependent
 - Electrolysis Chemistry
 - Production efficiency requirements
- State of reactant storage (cryogenic vs compressed) not relevant to electrolysis stack operation
 - Infrastructure Balance of Plant between stack and storage impacted, but stack is not

Requires Input Power



Unit Cell Electrolysis Performance



Reactant Generation

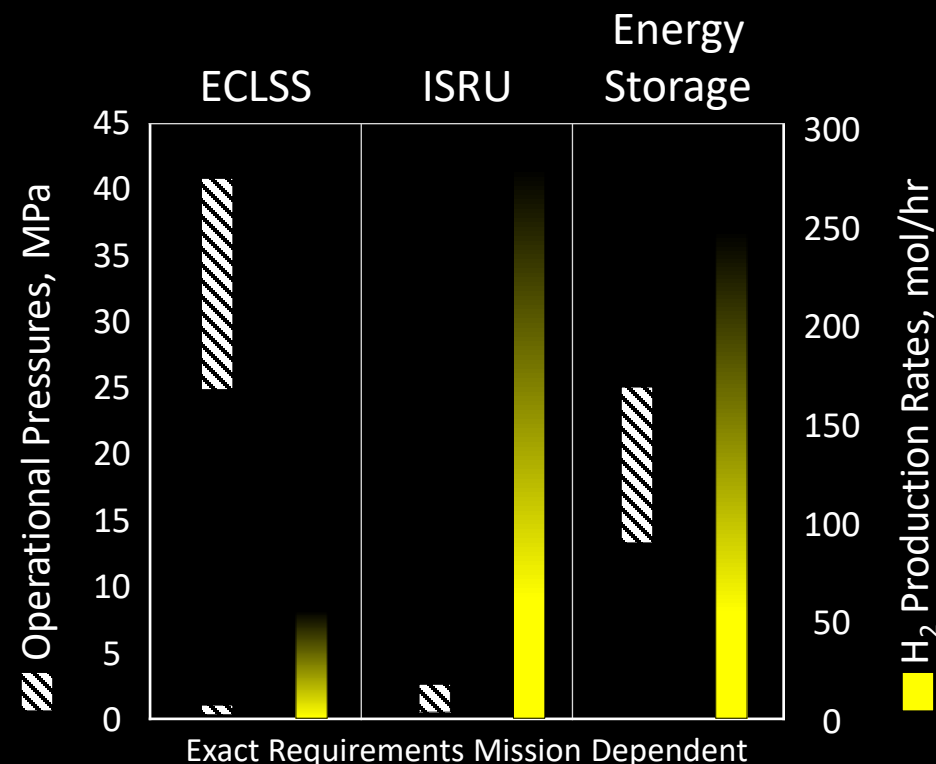
Electrolysis

- *Electrochemically dissociate water into gaseous hydrogen and oxygen*
- **ECLSS**
 - *Unbalanced Design ($H_2 \ll O_2$)*
 - *Unmet long-term requirements for reliability, life, or H_2 sensors stability*
- **Energy Storage**
 - *Balance Design ($H_2 \approx O_2$)*
 - *Unmet long-term requirements for performance, reliability, life, sensors availability, sensor stability*
- **ISRU**
 - *Balance Design ($H_2 \approx O_2$)*
 - *Unmet long-term requirements for performance, reliability, or life*
 - *Tolerate contaminated water sources to minimize pre-conditioning requirements*

Water Mining and Processing

- *Recover raw materials from local sources*
 - *Regolith Processing*
- **Contaminated Water Processing**
 - *Minimize water cleaning system complexity and mass*
 - *Remove inert contaminants (e.g. Ca^+ and Mg^+ salts)*
 - *Remove chemically active contaminants (e.g. H_2S , NH_3 , H_2CO_3 , H_2SO_4 , Hg , Methanol, etc.)*

Notional Electrolysis Requirements



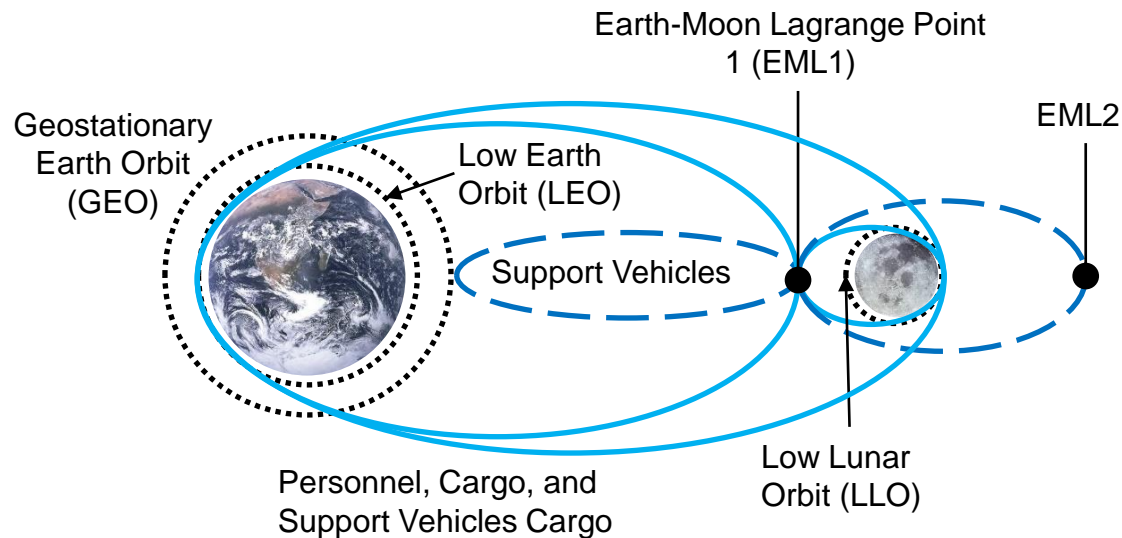
All applications Power and Mass Constrained

How Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)



Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

- Enable exploration by staging required resources in forward locations
 - Earth Orbit (LEO, GEO)
 - LaGrange Points (EML1 and EML2)
 - Lunar Orbit
 - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

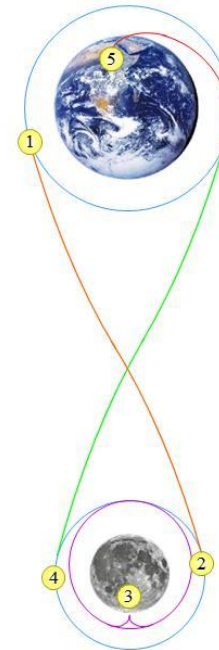


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Moon Lander: Surface to NRHO

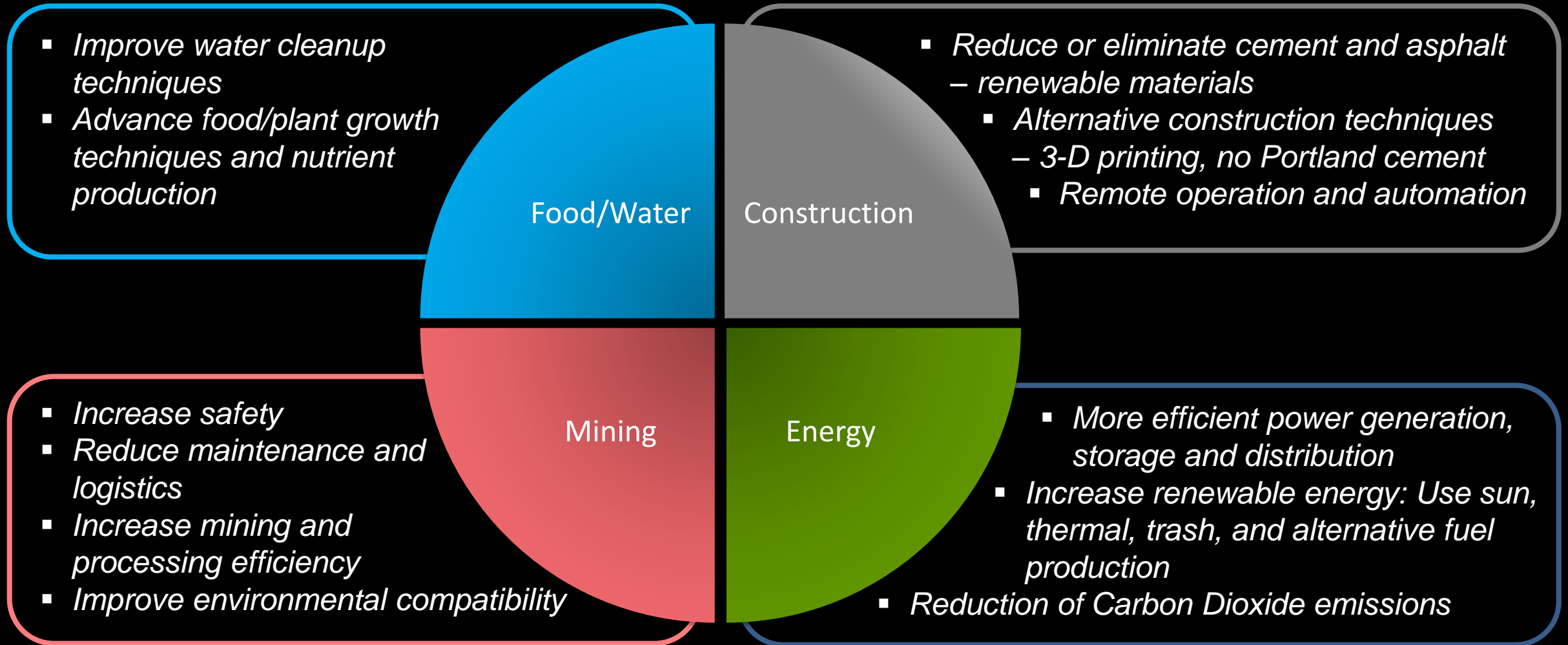
- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



- 1 LEO
- 2 Lunar Destination Orbit
- 3 Lunar Surface
- 4 Lunar Rendezvous Orbit
- 5 Earth Surface

A Kilogram of Mass Delivered Here...	...Adds This Much Initial Architecture Mass in LEO	...Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

ISRU Synergistic with Terrestrial Needs



Promote **Reduction, Reuse, Recycle, Repair, Reclamation**
...for benefit of Earth, and living in Space.

Reactant Transfer and Storage

Transporting Hydrogen and Oxygen through cis-lunar space is very complicated

Variable Storage times

Supply vehicle can launch days to months before target vehicle

No buoyancy to help separate the cryogenic fluids from evolved gases

Complex multi-phase fluid flow

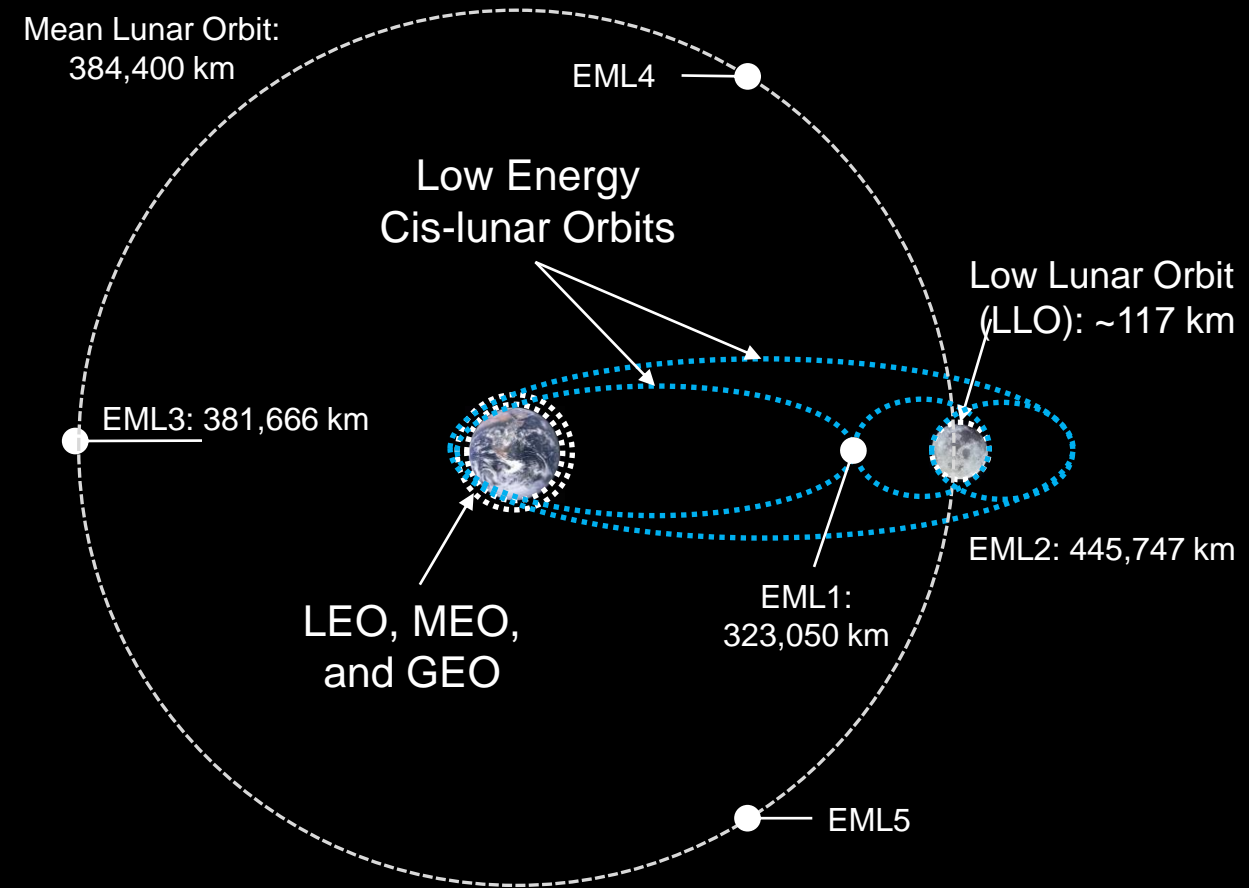
Complex Thermal Environment

Very low H_2 liquid transition temperatures

Radiation only available heat sink

Very large temperature differences between sun-facing and deep-space facing surfaces

Challenging to pre-cool target system while retaining cryogenic fluids within the system



Lagrange Points of the Earth-Moon (EM) System as viewed from above the Earth-Moon Orbital Plane

Image Not to Scale

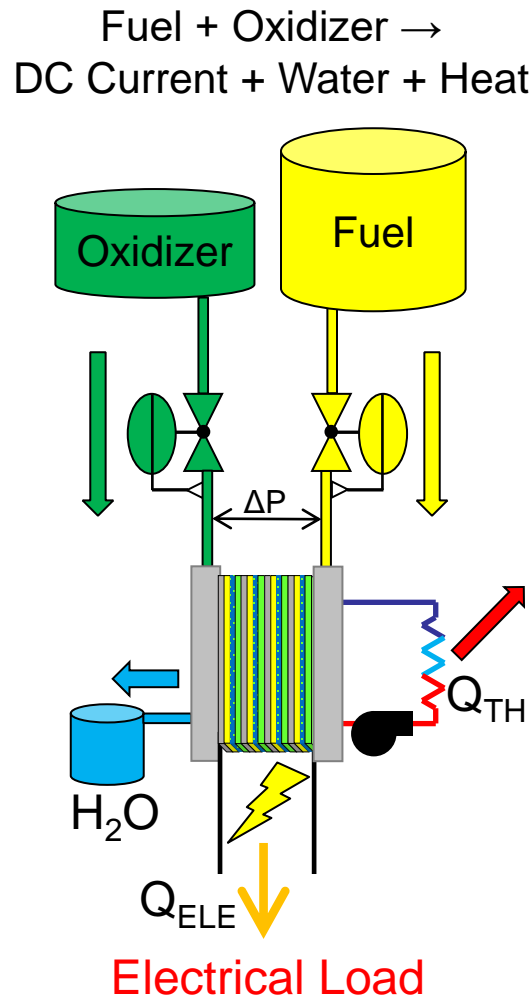
Basic Electrochemical Systems: Fuel Cell



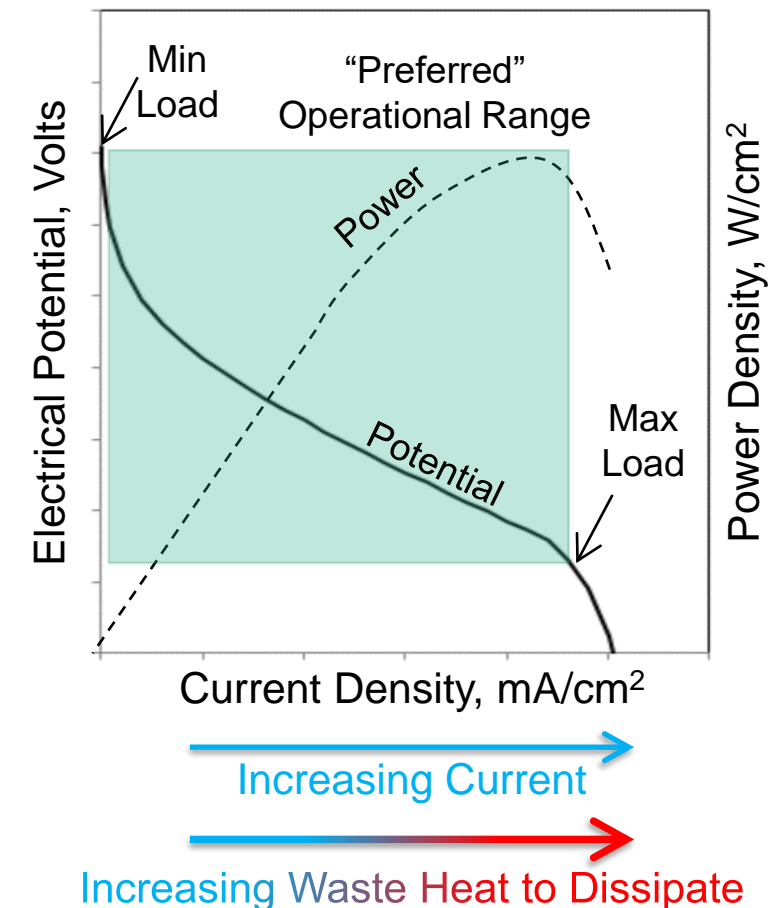
Fuel Cell

- Primary electrical **current** source (voltage indicates conversion efficiency)
- Fluidic analogy
 - Fuel cell ~ fluid pump
 - Current ~ fluid flow rate
 - Voltage ~ fluid pressure
- Pure water byproduct (molecularly pure at catalyst site)
- Water state (gas / vapor) dependent on Fuel Cell Chemistry
- State of reactant storage (cryogenic vs compressed) not relevant to fuel cell stack operation
 - Balance of Plant between stack and storage impacted, but stack is not

Discharge Power Only



Unit Cell Fuel Cell Performance



Primary Fuel Cells vs. Primary Battery

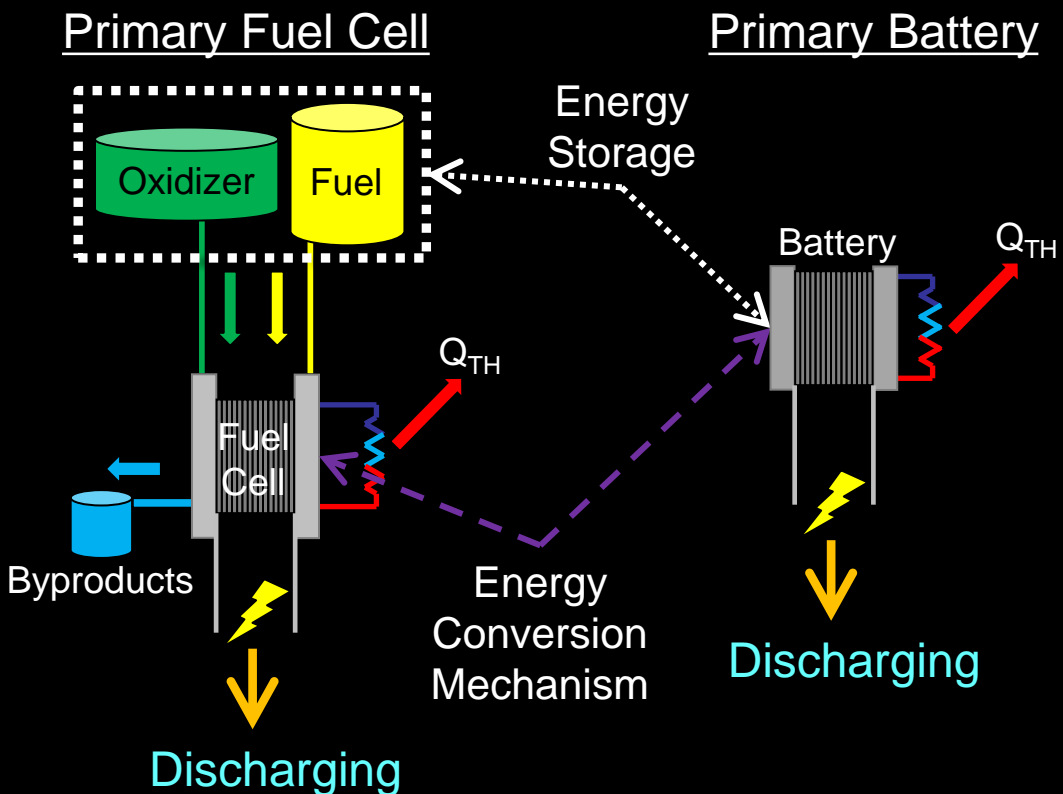
Electrical Power to enable and augment exploration activities



Primary Metric = Specific Power (W / kg)

Batteries store energy intimately with the energy conversion mechanism

Primary fuel cells store energy remotely from the energy conversion mechanism



- **Different** Hazards and Mitigations
 - Batteries sensitive to Thermal Runaway
 - Fuel Cells sensitive to Material Compatibility and Process Fluid management issues
- **Different** Voltage to State-of-Charge (SoC) relationships
 - Battery voltage dependent on quantity of stored energy
 - Fuel Cell voltage independent of quantity of stored energy
- **Different** Scalability
 - Battery system specific energy determined by chemistry and packaging
 - Fuel Cell system specific energy determined by quantity of reactants and packaging

Regenerative Fuel Cell vs. Rechargeable Battery



Energy Storage enabling and augmenting exploration activities

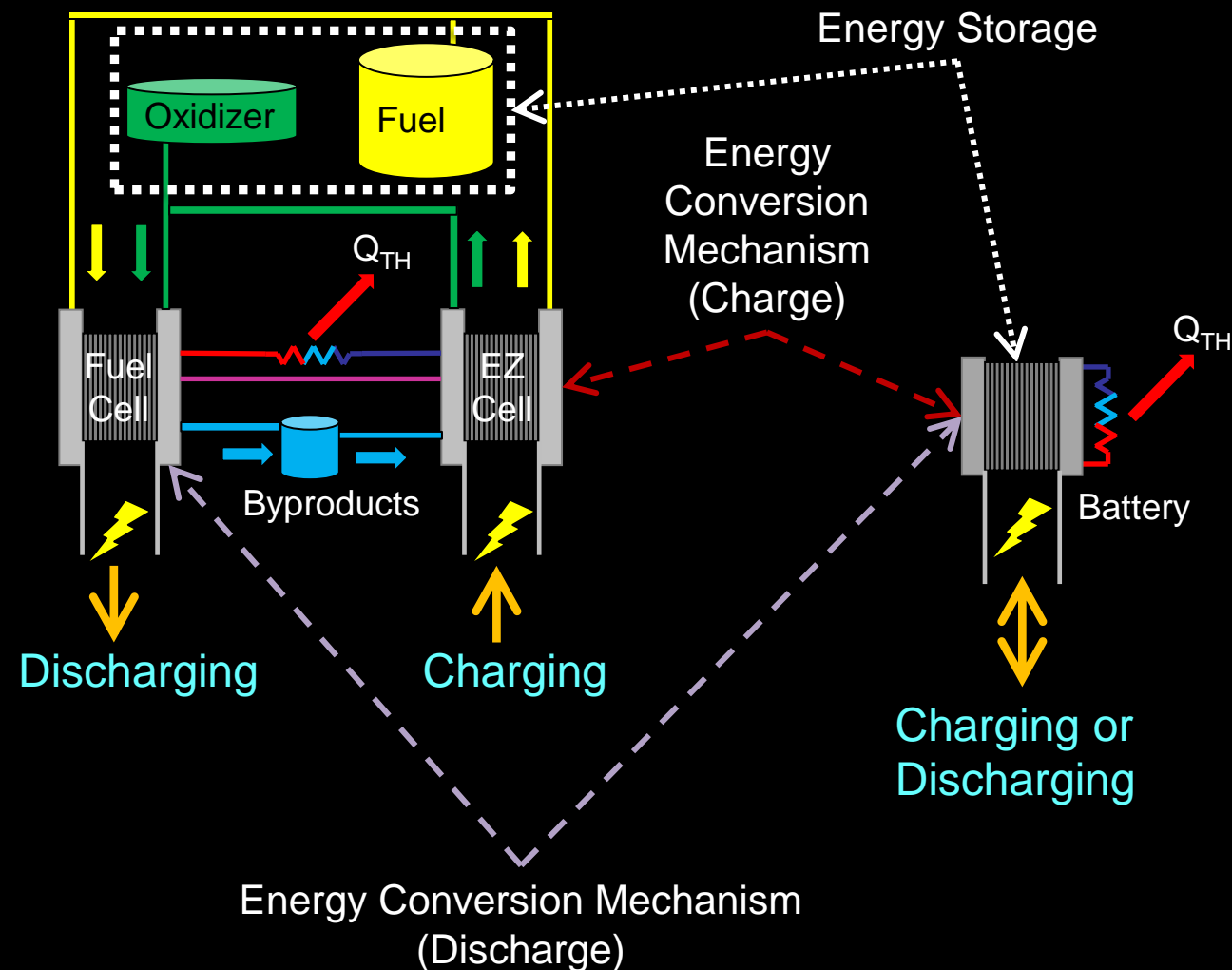
Regenerative Fuel Cell

Rechargeable Battery

Primary Metric = Specific Energy (W·hr / kg)

Rechargeable batteries store energy intimately with the energy conversion mechanism

Regenerative fuel cells (RFCs) store energy remotely from the energy conversion mechanisms



- **Different** Hazards and Mitigations
 - Batteries sensitive to Thermal Runaway
 - RFC have very complicated supporting systems
- **Different** Voltage to State-of-Charge (SoC) relationships
 - Rechargeable battery voltage **dependent** on quantity of stored energy
 - RFC discharge voltage **independent** of quantity of stored energy
- **Different** Recharge/Discharge capabilities
 - Battery rates determined by chemistry and SoC
 - Fuel Cell and electrolyzer independently “tunable” for mission location

Power Generation and Storage



Propellants

- NASA currently requires between 3 to 10 million pounds LH_2 per year but likely to increase with launch cadence
- KSC and SSC require 5 to 12 commercial tankers / day during LH_2 fill to minimize schedule impacts
- Space Launch Systems (SLS)
 - 539,000 gal LH_2 capacity
 - Burn rate is $\sim 67,375$ gal LH_2 /min
- Commercial Cis-Lunar Transportation industry estimated to need $\sim 50,000$ to $\sim 275,000$ kg LH_2 /year



The Space Launch System rocket core stage comes alive during the Green Run hot fire test on 16 Jan. 2021 at NASA's Stennis Space Center near Bay St. Louis, Mississippi.

Image Credit: NASA

Hydrogen-based fuel cells

- Lunar/Mars surface systems
 - ≤ 10 kW primary fuel cell modules fueled by H_2/O_2 or CH_4/O_2
 - $36 \text{ kW}\cdot\text{hr}_{\text{net}}$ to $1 \text{ MW}\cdot\text{hr}_{\text{net}}$ energy storage using H_2/O_2 regenerative fuel cell systems
- Urban Air Mobility
 - Multiple air-based primary fuel cell systems studies for systems fueled by H_2 , CH_4 , and bio-fuels (e.g. X-57)
 - Hydrogen storage technologies for aircraft (e.g. CHEETAH)



NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California.

Credits: NASA Photo / Lauren Hughes

Known Aeronautic Technical Gaps

1. Thermal management:

- High Power applications = large thermal loads
- Electric aircraft have multiple distributed thermal loads
- Advanced Hydrogen combustion technologies have localized thermal loads

2. Power Management and Distribution

- High Electrical Current
- High Power / High Voltage Conversion
- Wiring mass

3. On-board Hydrogen management

- Cryogenic Storage
- Hydrogen Monitoring
- Hydrogen Materials

4. System Integration

- Putting it all together in a cost-effective package for commercial applications



Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)



Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) program to develop, mature, and design disruptive technologies for electric commercial aviation.

- Provide a direct line-of-sight path to
 - Meet/exceed aviation goals for alternative propulsion and energy options
 - An aircraft system with a quiet, efficient propulsion system that produces zero CO₂, NO_x, and particulate emissions
- Research associated technologies
 - Distributed aero-propulsion system integration
 - High-efficiency electrochemical power conversion
 - Flight-weight electric machines and power electronics,
 - Materials and systems for superconducting high-efficiency power transmission
 - Methods for complex system integration and optimization.
 - Unconventional energy storage and power generation architectures (e.g. liquid hydrogen fuel and fuel cell systems)
- Identify Technology Gaps for future research



Principal Investigator: Phillip Ansell

Lead Organization: University of Illinois

Supporting Organizations:

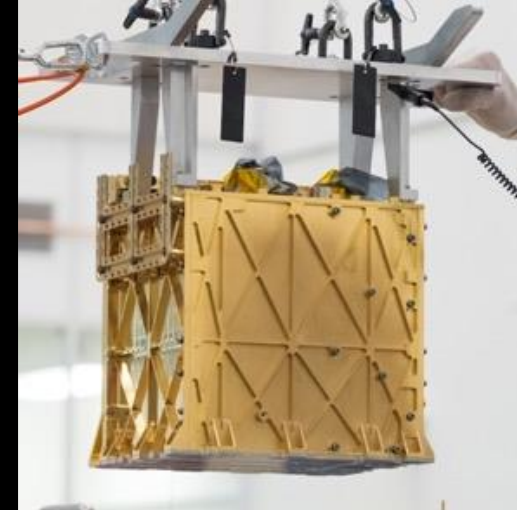
- Boeing
- Chicago State University
- General Electric (GE)
- Massachusetts Institute of Technology (MIT)
- Ohio State University
- Rensselaer Polytechnic Institute
- University of Arkansas
- University of Dayton

Presentation Summary

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Mars Oxygen ISRU Experiment (MOXIE)

Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars
Apr. 2021.



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Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage.



Questions can be sent via e-mail to

- John Cavolowsky (john.a.cavolowsky@nasa.gov)
- Ian Jakupca (ian.j.jakupca@nasa.gov)



Thank you for your attention.